CONCEPTUAL DECISION SUPPORT SYSTEM TO OPTIMISE STRATEGIC DECISIONS IN BIOMASS-FOR-BIOENERGY SUPPLY CHAINS

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Abstract

This paper presents a conceptual decision support system (DSS) to optimise strategic decisions in the biomass-for-bioenergy (B4B) supply chain. This DSS combines three integrated modules: (i) a generic and flexible database, (ii) an optimisation module and (iii) a query tool. The non-spatial component of the *database* covers the possible product types and the possible techniques to harvest, collect, store, pre-treat and convert biomass to bioenergy with their attributes on the one hand, and their mutual relationships and possible sequences on the other hand. Spatial information regarding the (multi-modal) transportation network and the location of the (potential) biomass production sites, storage facilities and conversion facilities are maintained in the spatial component of the database. The *optimisation module* comprises a mixed integer linear programming (MILP) model to select the optimal location, technology and capacity of operations and operation facilities. Simultaneously, the MILP model determines the optimal allocation of raw biomass materials, intermediate products and by-products from the biomass production site to operation facilities and between operation facilities. These strategic decisions are optimised regarding economic, energetic or environmental objectives and are restricted by the biomass-for-bioenergy supply chain and the transportation network defined in the database module. The *query tool* (developed in a GIS software) allows the user to organise and pre-process the source data and visualise and post-process the results. The functionalities of the conceptual DSS are illustrated by means of a simplified B4B supply chain based on low input high diversity (LIHD) biomass systems in the province of Limburg (Belgium).

Introduction

By 2035, the global energy consumption is expected to amount to 812 EJ (EIA, 2011). This will be a growth by 53 % in comparison to 2008 (532 EJ) (EIA, 2011). This increase in energy use may further boost the emission of greenhouse gases (GHG) (IPCC, 2007), the depletion of fossil resources and the geographic energy dependency (Cherubini and StrØmman, 2011). To counteract these trends, research initiatives rise to define the potential of alternative and renewable energy sources (Cherubini and StrØmman, 2011). Bioenergy is anticipated to play a dominant role (IPCC, 2011) owing to the versatility of biomass, the possibility to store and convert it to energy on-demand (Rentizelas et al., 2009).

However, the use of biomass as an energy source is discouraged due to a variety of barriers and uncertainties associated with the international trade and sustainable and efficient production of biomass resources and bioenergy (Bravo et al., 2012). The high costs related to the operations for handling and transport of biomass from the point of harvesting to the delivery of the products to the conversion facility are among the most decisive hurdles (Rentizelas et al., 2009). These costs cannot be avoided since they are indispensable to deal with the typical characteristics of biomass (e.g. spatial fragmentation, seasonal and weather related availability, high moisture content, low energy content and low bulk density) (Gold and Seuring, 2011; Rentizelas et al., 2009; Wee et al., 2012).

To overcome these barriers and to support the development of a strong bioenergy sector, sustainable bioenergy pathways need to be assessed. Therefore, operations research (OR) is regularly applied to define (a) the optimal biomass type to be converted, (b) the best way to transport, pre-treat and store biomass at operational, tactical and strategic level and/or (c) the optimal use of the conversion technologies (Wee et al., 2012). In order to identify the trade-offs between products and operations, all impacts generated throughout a bioenergy product's life-cycle must be taken into account (Godard et al., 2013), a comprehensive approach is needed. However, the review of existing mathematical models optimising the biomass-for-bioenergy (B4B) supply chain indicates that the available OR models are case specific, consider only a definite part of the chain and/or incorporate far from all interrelationships between products and operations and between operations mutually (De Meyer et al., in review). Therefore, this paper presents a conceptual decision support system to optimise strategic decisions in any B4B supply chain in a comprehensive way.

Conceptual DSS architecture

To counteract the shortcomings of the existing models (De Meyer et al., in review), this paper presents a DSS to optimise strategic decisions in B4B supply chains which is applicable to all kinds of biomass supply chains and considers the relationships between products and operations and between operations mutually incorporating all impacts generated throughout the life cycle. This DSS consists of three integrated modules (Figure 1): (i) a database module, (ii) an optimisation module and (iii) a query module (De Meyer et al., 2012). The *database module* encompasses the database covering the non-spatial and spatial parameters required in the optimisation module. The *optimisation module* consists of a mixed integer linear programming (MILP) model to select the optimal location, technology and capacity of operation facilities. Simultaneously, the MILP model determines the optimal allocation of raw biomass materials, intermediate products and by-products from the biomass production site to operation facilities and between operation facilities. The *query module* is developed in a GIS software and allows users to organise and pre-process their source data and visualise and post-process their results.

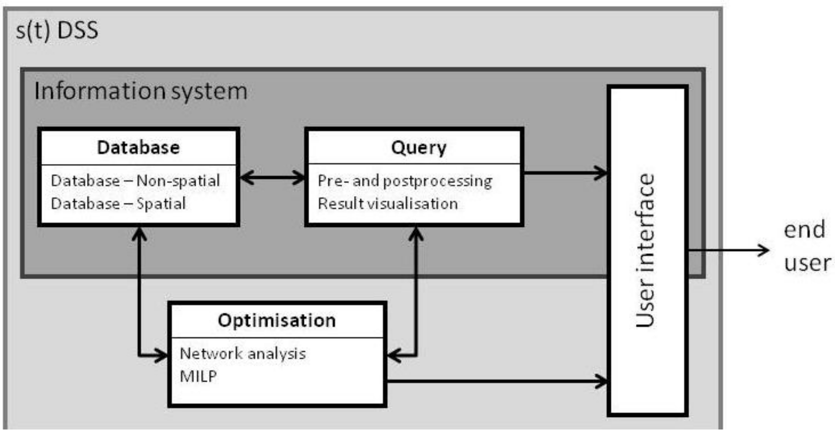

Figure 1 Conceptual architecture of the decision support system to optimise biomass supply chains (De Meyer et al., 2012)

Database module

Since the DSS aims to optimise all kinds of B4B supply chains, the data model is developed as a template for a functional database covering the parameters required in the optimisation module. Therefore, the data model needs to be generic to be able to describe all (or most) biomass supply chains (De Meyer et al., 2012). Additionally, the data model must be flexible to enable easy addition, deletion or change of objects, attributes and attribute values with minimal redundancy and without compromising the validity of the associations between the various object types (De Meyer et al., 2012).

To empower the generality and flexibility, the data model is divided into a non-spatial and a spatial component. The non-spatial component is the core of the data model and encompasses the non-spatial information covering the product types and the techniques to handle and transport biomass products with their attributes on the one hand and their mutual relationships and possible sequences on the other hand. To ensure that the data model approaches the B4B supply chain in a comprehensive way, the development of the data model is based on the results of a generic cradle-to-gate analysis. This analysis results in a conceptual model schematizing the potential sequences of operations in the B4B supply chain in which the conversion operation is considered as a black box with input of biomass and output of bioenergy and by-products (Figure 2). Six key operations can be distinguished from the point of harvesting raw materials to the delivery of the products to the conversion facility: i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy. Furthermore, after conversion rest products can be fed back into the supply process. An extended description of the non-spatial component of the data model is available in De Meyer et al. (2012).

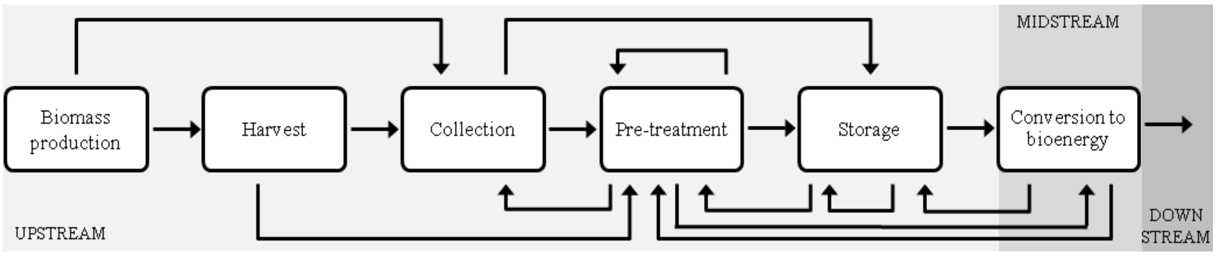

Figure 2 Conceptual model representing the potential sequences of operations in the B4B supply chain (a box corresponds with the operation and an arrow indicates the product flow between operations) (De Meyer et al., 2013b).

To fill the non-spatial component of the data model, users perform a life cycle inventory analysis (LCI) according to the conceptual model presented in figure 2. This LCI allows to identify the products and operations included in the product system to be analysed (De Meyer et al., 2013a). Once the product system has been defined each product and operation in the database is characterised by attributes related to energy use, economic cost and GHG emissions (indicated by the Global Warming Potential (GWP) calculated with IPCC's Fourth Assessment Report's factor for 100 years). Data collection and assumptions are based on databases such as ecoinvent® (Ecoinvent Centre, 2007), as well as peer-reviewed literature and expert opinions.

The spatial component is linked to a geographic information system (GIS) and contains the geospatial information to define the (multi-modal) transportation network. Furthermore, the spatial component summarises the geospatial coordinates and characteristics of the (potential) biomass production sites, storage facilities and conversion facilities.

Optimisation module

The optimisation module combines the typical GIS-based network analysis functions and a mathematical model to determine the optimal strategic design of the defined B4B supply chain. The GIS-based network analysis functions are mainly applied to calculate the shortest distance between biomass production sites and operation facilities and between operation facilities mutually. The mathematical model selects the optimal location, technology and capacity of storage, pre-treatment and conversion facilities in combination with the optimal technology to harvest and collect the product. Simultaneously, the mathematical model determines the optimal allocation of raw biomass materials, intermediate products and by-products from biomass production sites to the operation facilities and between operation facilities mutually. The goal of the proposed model is to account for supply chain restrictions, the available multimodal transportation network and the corresponding interrelationships between products and operations and between operations.

The mathematical model is designed as a transhipment problem (Winston, 2003) in which:

- The supply node corresponds to a biomass production site allowing harvest, collection and pre-treatment operations;
- The transhipment node corresponds to a storage site to store (and potentially pre-treat) raw biomass materials, intermediate products and/or by-products; and
- The demand node corresponds to a conversion site hosting pre-treatment, storage and conversion operations.

Between nodes product flow and transportation occurs. Additionally, the mathematical model enables by-products (e.g. digestate) to re-enter the supply chain for subsequent conversion to bio-energy or for alternative use (e.g. soil fertilizer).

Based on these principles, a mixed integer linear programming (MILP) model has been developed. The decision whether or not a storage or conversion facility with specified type and capacity is open at a location, and whether or not a harvest, collection or pre-treatment operation is performed at the biomass production site, a storage site and/or a conversion site are defined as binary and integer variables. The product flows between the different operations and sites are defined as continuous variables. Constraints define supply restrictions (e.g. mass balances, capacity of equipment and facilities) and the interrelationships between operations. The MILP model allows optimisation according to one out of three objectives; i.e. the cumulative annualized energy output, cumulative annualized profit and annualized cumulative GWP. The economic and energetic objectives are similar in which the "gain" depends on the amount of energy produced by the conversion facilities and the "loss" is defined by the required inputs for handling and transporting products and managing operation sites and equipment. The annualized cumulative GWP only considers the emissions during handling and transporting the biomass and management of storage and conversion sites. An extended description of the MILP model is given in De Meyer et al. (2013b).

Query module

The query module is developed in a GIS and enables users to organise and pre-process the initial spatial information (e.g. transportation network and location of biomass production sites, storage facilities and conversion facilities) and to visualise and post-process the optimisation results (e.g. optimal location of operation facilities and allocation of products).

Use case

To illustrate the presented approach, the conceptual DSS is used to define the optimal strategic design of a B4B supply chain in which the biomass is derived from low input high diversity (LIHD) biomass systems (e.g. (semi-) natural grasslands, heath lands) in the Belgian province Limburg (2422 km²). Forty six biomass production sites have been derived from a biological value map (Vriens et al., 2011) by selecting the sites characterised as grass or brushwood with an area of at least 50 ha (36167 ha of grass and 2536 ha of brushwood). At these biomass production sites, biomass can be harvested with a disc mower or a flail mower and collected by tractor with trailer or a mow-load combination. Thirteen potential storage sites (piles or hangars) are located according to the nearness of a highway access point, the need of a transhipment point between tractor and truck to allow further transport or the density of biomass production sites. One industrial anaerobic digester (IAD) is located in the north-east of Limburg, while three farm scale anaerobic digesters (FAD) are scattered over the study area. All digesters are registered by the Flemish compost organisation (VLACO). At all biomass production sites and at all operation facilities chopping and drying operations are allowed to deal with the typical characteristics of grass and brushwood. For this use case, attribute values are adopted or derived from scientific publications (o.a. Suurs et al., 2002), LCA databases and energy statistics. A more detailed description of the use case including the attribute values is given in De Meyer et al. (2013a and 2013b).

Two scenarios are presented to investigate the differences in strategic biomass supply due to centralized (scenario 1) and distributed (scenario 2) production of bioenergy. Scenario 1 optimises the strategic supply design considering the anaerobe digesters in Limburg as registered by VLACO (i.e. one IAD and three FAD). Scenario 2 considers four FAD with an electric capacity of 8000 MWh_e at the same sites as the anaerobe digesters in scenario 1. It is hypothesised that, in scenario 2, the MILP model will distribute the production of bioenergy between different conversion facilities instead of centralised production in one conversion facility. Both scenarios assume a total heat production of at least 7536 MWh (~27130 GJ) and a total electricity production of at least 15137 MWh (~54493 GJ). This energy demand is determined according to the total heat and electricity demand in Limburg, the obligation to produce 13% of Belgium's final energy consumption from renewable energy sources (EU Renewable Energy Directive) and the fact that biogas comprises 8% of the produced renewable energy (www.energiesparen.be).

Table 1 summarises the results of scenario 1 and scenario 2 when optimised according to one out of the three objectives; i.e. maximal energy output (A), maximal financial profit (B) and minimal GWP (C). When the biomass supply chain is optimised for one objective (number in bold), the value for the other two objectives is also calculated. The results (e.g. harvested biomass production sites, used conversion facilities, allocation pathes, etc.) are visualised spatially in figure 3.

Table 1 Summary of the results of the scenario analysis (cfr. De Meyer et al., 2013a and 2013b) (BW = brushwood, GR = grass, BPS = biomass production site, CL = conversion site)

	SCENARIO 1			**SCENARIO 2**		
	Energy (A)	Profit (B)	GWP (C)	Energy (A)	Profit (B)	GWP (C)
Total E_{out} (GJ y^{-1})	**117049**	111624	106307	**118407**	112284	108885
E generated (GJ y^{-1})	140868	140868	129062	140269	140269	129821
E used (GJ y^{-1})	23819	29244	22755	21862	27985	20936
Total profit (€ y^{-1})	6022147	**6047466**	5485617	6200654	**6259865**	5720363
Total income (€ y^{-1})		6920412			6888077	
Total cost (€ y^{-1})	6920412	872946	6340401	6888077	628212	6375026
	898265		854784	687423		654663
Total GWP (kg CO_2 eq y^{-1})	1878906	1957138	**1866087**	1438876	1531820	**1429287**
Biomass	BW: 2 GR: 17	BW: 2 GR: 17	BW: 2 GR: 13	BW: 2 GR: 19	BW: 2 GR: 20	BW: 2 GR: 17
Storage	0	0	0	0	0	0
Conversion	1 IAD	1 IAD	1 IAD	3 FAD	3 FAD	3 FAD
Harvest	Flail	BW: flail GR: disc	Flail	Flail	BW: flail GR: disc	Flail
Collection	Mow-load	BR: Mow-load GR: trailer	Mow-load	Mow-load	BR: Mow-load GR: trailer	Mow-load
Pre-treatment	Chop at CS	BR: chop at BPS GR: chop at CS	Chop at CS	Chop at CS	BR: chop at BPS GR: chop at CS	Chop at CS
Transport	Truck	Tractor Truck	Truck	Truck	Tractor Truck	Truck
Calculation time (s)	48	21	19	366	24	12

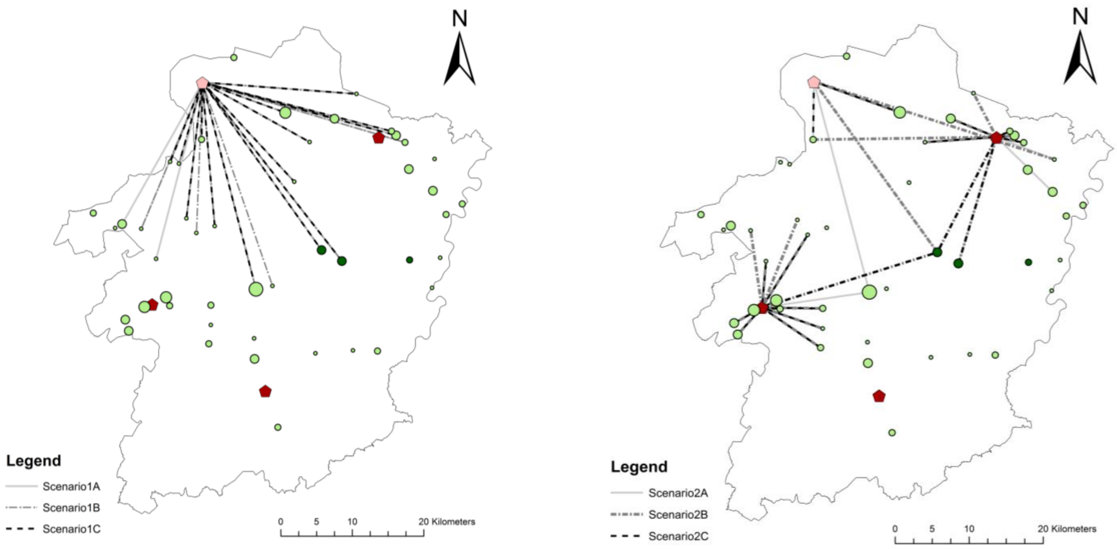

Figure 3 Visualization of the location – allocation result of scenario 1 and scenario 2 (adopted from De Meyer et al., 2013a and 2013b)

In scenario 1, the capacity of the IAD (i.e. 51686 MWh_{th} and 43072 MWh_{e}) easily meets the assumed heat and electricity demand. Therefore, all biomass is transported to the IAD (Figure 3a). Additionally, this centralised energy production is induced by the constraints defining the required moisture content of the biomass mixture in the IAD (i.e. between 60% and 80%). This higher range excludes the need for additional drying operations in comparison with the FAD, which requires additional drying operations to meet the maximum moisture content of 65%. These extra operations bring along additional energy inputs, costs and emissions when the FAD is used.

In scenario 2, three out of four FAD are selected to meet the heat and electricity demand. Furthermore, a larger number of biomass production sites are harvested to meet the required minimum biomass input at each facility. In comparison to scenario 1, biomass from one biomass production site is allocated to several conversion facilities. In the case of brushwood, the biomass is divided between the FAD to meet the moisture content requirement of the digested biomass mixture. Additionally, scenario 2 results in a higher cumulative energy output, a higher cumulative profit and a lower GWP than scenario 1. This likely owes to the decentralized conversion of biomass, which reduces the transport distances resulting in lower amount of energy consumed, money spent and GHG emitted (Table 1).

Table 1 indicates that the energetic and environmental objectives result in the same supply operations, while the economic objective distinguishes operations for grass and operations for brushwood. This also explains that the cumulative energy output and cumulative profit in the solutions of objectives A and B differ while the amount of energy and income generated by the conversion facilities are equal. Figure 3 approves that in both scenarios the allocation pattern differs depending on the objective to be optimised. This difference can be attributed to the differences between the effects of the transport attribute values (energy input, cost and GWP). Furthermore, all harvested biomass production sites are located in the vicinity of the selected conversion facilities. Also here, the transport distance is the most influencing factor. Additionally it is clear from table 1 and figure 3 that storage facilities are not included in the optimal solution because the extra cost to manage the storage site is higher than the cost to transport the products directly to the conversion facility. This relates to the relatively small scale of the use case.

Conclusion and future research opportunities

The development of a strong bioenergy sector and the use of biomass as an energy source is discouraged due to a variety of barriers and uncertainties related to international trade and sustainable and efficient production of biomass resources and bioenergy (Bravo et al., 2012). One of the most decisive hurdles is the complexity and cost of the (upstream) B4B supply chain (Rentizelas et al., 2009). Therefore, this paper introduces a DSS to optimise strategic decisions in B4B supply chains which is applicable to all kinds of biomass supply chains and considers the relationships between products and operations and between operations mutually incorporating all impacts generated throughout the B4B life cycle. This DSS consists of a generic and flexible database to store the required parameters, a mixed integer linear programming model to determine the optimal design of the B4B supply chain and a query tool to organise and pre-process the source data and visualise and post-process the results.

This scenario analysis in combination with previous experiences indicate that this conceptual DSS can be applied to determine the most optimal strategic design of a B4B supply chain considering a range of alternative products and operations. Moreover, the DSS can be an inspiring tool to investigate the consequences of policy decisions and investment options, such as introducing new biomass materials or additional conversion facilities. However, the user must be aware that the results indicate a direction of change between scenarios, rather than presenting exact values because the attribute values adopted or derived from literature resources are often burdened by uncertainties.

Future work entails the elaboration of the MILP model to combine multiple objectives simultaneously in the optimisation process incorporating all elements of sustainability. Also, the MILP model will be expanded to support the optimisation of the supply chain considering the temporal variability in supply of biomass and demand of bioenergy. In this temporal variability the cyclicity in the production of biomass will be considered for determining a.o. the optimal moment to harvest the biomass. This cyclicity implies that mowing today affects the availability and composition of tomorrow's biomass. Probably, a simulation tool must be added to the conceptual DSS to include this time influence. Finally, the DSS can also be further elaborated by including extra information on the life cycle of biomass, such as land use and land use change which remain on the forefront of the debate on sustainable bioenergy.

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